

Langmuir probe measurement in a radio frequency inductively coupled argon plasma

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A Langmuir probe diagnostic system is constructed to measure the plasma properties in a radio frequency (RF) inductively coupled Argon plasma. A passive compensation is incorporated into the Langmuir probe to provide the high impedance to the probe tip in the fundamental drive frequency of 13.56 MHz. This will enable the probe tip to follow the RF fluctuation in the plasma and allows the “dc” probe characteristic to be measured. The properties of the RF inductively coupled Argon plasma are measured in the pressure range of 0.01 mbar–0.4 mbar and the RF incident power from 20 W–280 W. The radial and axial distributions of the RF Argon plasma are also studied. Comparison of the results from the Langmuir probes with compensation and without compensation demonstrates the effect of the compensating component.

I. INTRODUCTION

Detailed knowledge of the particle distribution functions is usually required for their validity in basic plasma experiments and plasma diagnostics are needed to determine those details. At another extreme, such as in plasma processing control, it suffices to have an indication that the device has the same plasma characteristics as of a previous occasion and not necessarily to know the details of the characteristics. The Langmuir probe offers a simple way to determine the plasma properties of the discharge. The current collected is measured as the probe is biased at different voltages with respect to the plasma potential. The current-voltage (I - V) curve obtained can be related to the localized plasma parameters. However, care has to be taken such that the insertion of the probe produces none or negligible perturbation to the local surroundings, else it can lead to erroneous interpretation.

In RF inductively coupled systems, the plasma potential V_s is often modulated at the drive frequency [1]. This modulation results in a time-averaged probe current measured against a time-averaged probe potential. Thus, deviation from the true shape arises in the I - V curve or “dc” I - V characteristic of the probe. It is thus necessary to make the RF electrical impedance at the probe tip to be much higher than the impedance of the probe sheath. High impedance can be achieved by incorporating properly designed RF tuned circuits and chokes.

It is the purpose of this work to construct a Langmuir probe diagnostic system to measure the plasma parameters (T_e, n_e) as well as the plasma density spatial distribution in an RF inductively coupled Argon plasma reactor. Comparison is also made to the

I - V characteristic of the probe with and without the passive RF filter to deduce the effectiveness of the filter.

II. EXPERIMENTAL SETUP

The RF plasma is excited at 13.56 MHz through a planar spiral coil placed below the quartz plate outside a 0.02 m³ cylindrical reactor chamber. The planar coil is coupled to a 600 W, 50 Ω RF generator via an impedance matching network. The Langmuir probe is inserted into the reactor chamber through one of the 12 diagnostic/view ports. Argon gas is allowed to flow continuously while a constant pressure is maintained in the chamber by controlling the gas in-flow and pump-out rates.

The Langmuir probe constructed is shown schematically in Fig. 1. Its tip is made of molybdenum wire of 0.8 mm in diameter and 1 mm in length (exposed part). A passive RF filter is connected to the tip with values of capacitance and inductance of 352 pF and 0.39 μ H respectively such that high impedance occurs at resonant frequency of 13.58 MHz ($\pm 10\%$). This aims to suppress the interference in the measured I - V curve brought about by the RF fluctuations of the plasma potential at the fundamental drive frequency of 13.56 MHz.

The probe is biased with an amplified triangular wave of 90 V peak-to-peak. A “dc” offset is added such that the probe voltage sweeps from –60 V to 30 V at a frequency of 23 Hz. The current is monitored as a differential voltage across a 47 k Ω resistor. The schematic diagram of the probe data acquisition is shown in the Fig. 2. At each input to the oscilloscope a low pass filter is connected to eliminate RF noise picked up by the conducting cables.

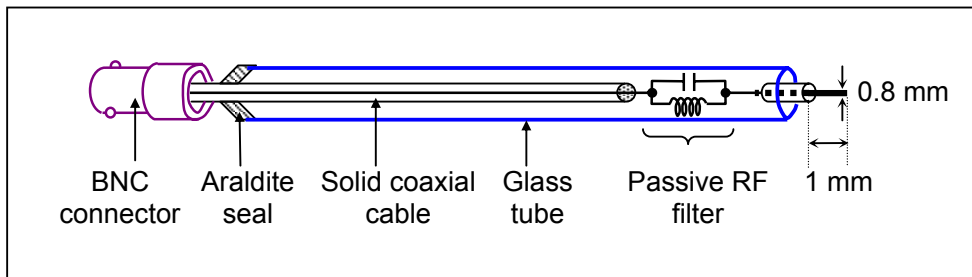


FIG. 1. Constructed Langmuir probe with high RF impedance component.

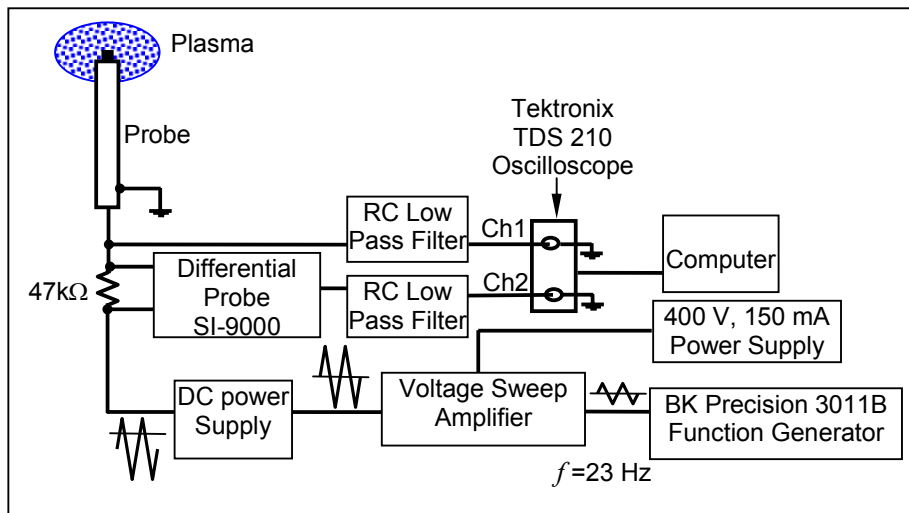


FIG. 2. Langmuir probe data acquisition setup.

III. RESULTS AND DISCUSSION

I - V curves of RF compensated (with RF filter) and uncompensated (without RF filter) Langmuir probes are shown in Fig. 3. These are obtained in 0.1 mbar Argon plasma at 100 W incident RF power. The retardation region of the I - V curve of the probe with filter is steeper than the one without. This is similar to those reported by other workers [2-5]. The shift of the floating potential of the probe towards more positive value indicates a decrease in the residual amplitude of the RF fluctuations due to the high RF impedance of the filter [6]. This will enable the probe tip to follow the RF fluctuations in the plasma but at the same time allows the undistorted “dc”

probe characteristic to be measured as the RF fluctuations are highly attenuated after the filter.

Figs. 4 and 5 show the electron temperature T_e and plasma density n_e respectively as functions of incident RF power for the compensated and uncompensated probes. T_e obtained by the uncompensated probe is higher while n_e is lower. When incident RF power is increased, n_e increases proportionately. This is because the increase in the incident RF power provides more energy to be transferred to create more ionization in discharge. T_e however falls with increasing incident RF power.

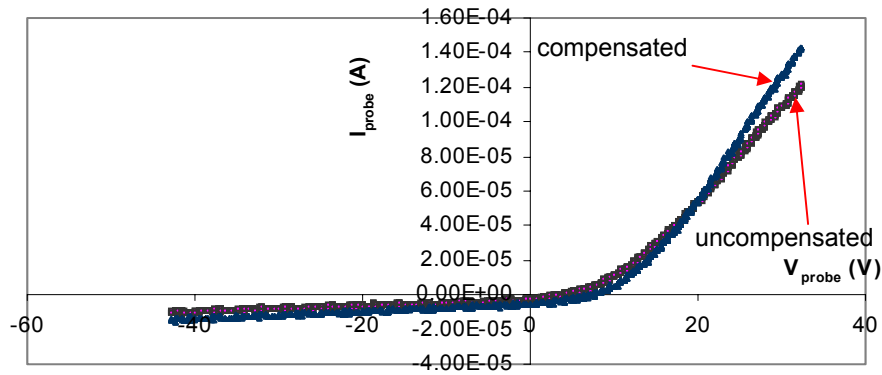


FIG. 3. I - V characteristic of the compensated and uncompensated Langmuir probes obtained in 0.1 mbar Argon plasma at 100 W incident RF power.

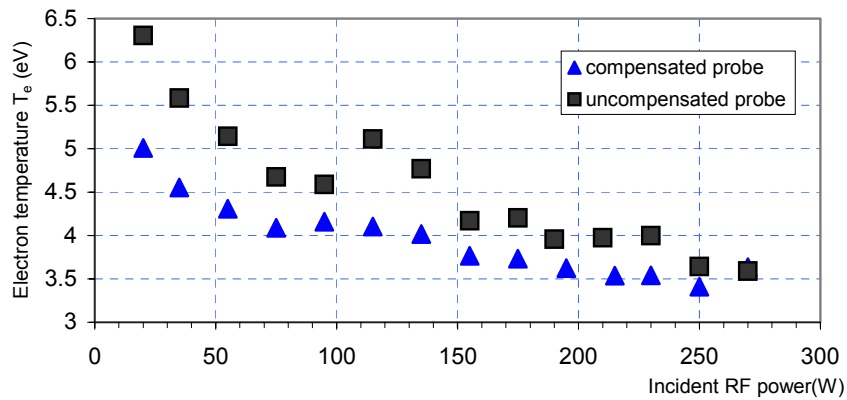


FIG. 4. Electron temperature T_e as a function of incident RF power for the compensated and uncompensated Langmuir probes in a 0.1 mbar Argon plasma.

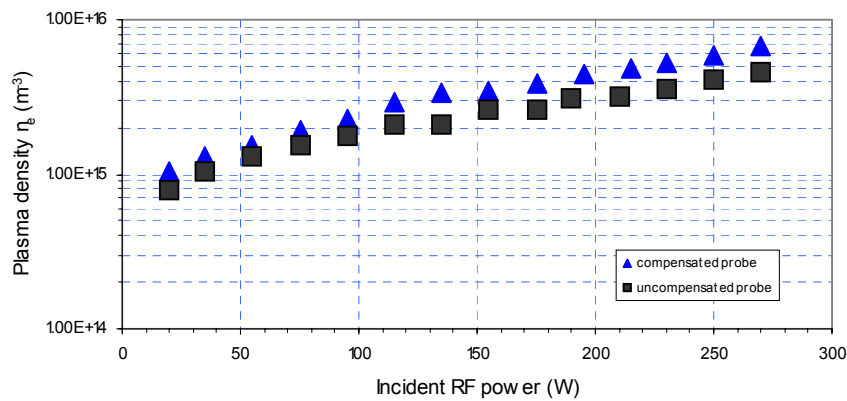


FIG. 5. Plasma density n_e as a function of incident RF power for the compensated and uncompensated Langmuir probes in a 0.1 mbar Argon plasma.

The dependences of the electron temperature and density on the incident RF power at different Argon pressures in the range of 0.01 mbar–0.4 mbar are shown in Figs. 6(a) and (b). In Fig. 6(a), T_e shows no obvious trend of change with pressure. It is likely that the uncertainty (as high as 25%) in determining the slope of the retardation region could have obscured the pressure dependence in T_e . Furthermore, the energy of the electrons may not subscribe to a totally Maxwellian distribution [5,7]. Many other workers [7-11] have actually shown T_e to be lower at higher pressures in ranges of pressures that extend to much lower pressures compared to this work.

The plasma density is determined from the ion saturation current as the low-current portion of the I - V characteristic of the probe is deemed to be least affected by the RF fluctuations [12]. The plasma density is observed to decrease with increase in Argon pressure (Fig. 6(b)). This observation differs from those reported in References [7-11] in which the density is higher at the higher pressure. However, the above observation agrees with Paranjpe *et al.* [5]. This decrease in plasma density as gas pressure increases can happen if elastic collisions become dominant with increase in pressure especially when the power dissipation to the plasma is low enough. Since the coupling of the coil to the plasma is sensitive to the distance between the coil and coupling window [9], less power is coupled to the plasma when the coil is further away from the window. In this experiment, the position of coil is 1.5 cm from the window which results in lower power coupled into the reactor chamber when compared to configuration with coil immediately close to quartz window. In fact, El-Fayoumi *et al.* [13] have shown that the B_z field in an evacuated chamber drops by ~30% at a distance of 1.5 cm from the plane of the planar coil. Lower power coupling means less energy for electrons to collide inelastically to create ionization processes. This is also the reason why the plasma density obtained in this experiment (at E-mode) is lower than those reported by other workers [7-11].

It is noted that measurement of electron temperature and density taken at 0.4 mbar is inaccurate as the mean free path at this pressure is beyond the applicability range of this Langmuir probe in which collisionless sheath has been assumed. Visual inspection shows the presence of a secondary glow around the probe at pressures > 0.4 mbar. Under this condition, the environment in the vicinity of the probe is believed to be strongly perturbed by the probe rendering the measurement invalid.

The preceding electron temperature and density shown were measured in the E-mode operation of the Argon RF discharge. For comparison, at Argon pressure of 0.01 mbar and higher incident RF power of 520 W in which the H-mode operation is observed, the measured electron temperature is 3.1 eV whilst the plasma density

is at $1.34 \times 10^{17} \text{ m}^{-3}$ (one to two orders of magnitude higher).

The spatial distribution of the plasma density in the axial direction away from the quartz surface ($z = 0 \text{ cm}$) is measured up to a distance of $z = 11.0 \text{ cm}$ at increments of 0.25 cm. The radial distribution of the plasma density is measured from the axis ($r = 0 \text{ cm}$) towards the wall of the chamber up to $r = 8.75 \text{ cm}$ at incremental distances of 0.25 cm; the probe tip is at 5.5 cm above the surface of the quartz plate. The repositioning of the probe in the chamber was done by shutting down the discharge before it is adjusted to a new position. Thus, care was taken to ensure that the same condition of the Argon plasma is maintained with each adjustment of the position. The radial and axial distributions of the plasma density are respectively shown in Figs. 7(a) and (b) for Argon discharge at 0.1 mbar and 100 W incident RF power. It is observed that the plasma density is distributed uniformly across the radial distance up to about 6 cm before falling steeply. The diameter of spiral planar coil is approximately 8.5 cm. Thus, the uniformity of the plasma density across the diameter of the spiral planar coil is assured. On the axial distribution which is shown in Fig. 6(b), the density increases sharply from the surface of the quartz window before reaching a maximum at $z = 1.5 \text{ cm}$ from the quartz plate. After that, it decreases gradually as the probe is moved further away from the window which is expected as the energizing field diminishes with increasing distance from the source (the planar coil). These spatial distributions observation is similar to those reported by Schwabedissen *et al.* [10] and Mahoney *et al.* [14].

IV. CONCLUSION

The constructed RF compensated Langmuir probe was shown to be successful in suppressing the effect of RF fluctuation of the plasma potential in the “dc” I - V probe characteristic to some extent. However, quantifying its effectiveness was not possible in the present setup and equipment available. The plasma parameters in the E-mode operation of the planar coil RF ICP Argon discharge have been measured for the range of incident RF power from 20 W to 280 W and pressure from 0.01 mbar to 0.1 mbar. (Data at 0.4 mbar are excluded as it was found to be inaccurate.) The measured electron temperature ranges from 3.5 eV to 5.0 eV and decreased with increasing incident RF power whereas no obvious trend of variation with pressure was obtained. The measured plasma density is between $8 \times 10^{14} \text{ m}^{-3}$ and $2 \times 10^{16} \text{ m}^{-3}$ and it increased with increasing incident RF power but decreased with the increasing pressure. These values are approximately one order of magnitude lower when compared to those reported by others and was attributed to the reduction in magnetic induction due to the position of the induction coil. From the spatial distribution of the plasma density

measurement, it can be concluded that uniform plasma can be obtained across the entire diameter of the spiral planar coil at $z = 5.5$ cm above the quartz window and the highest density is located on the axis at 1.5 cm above the surface of the quartz window.

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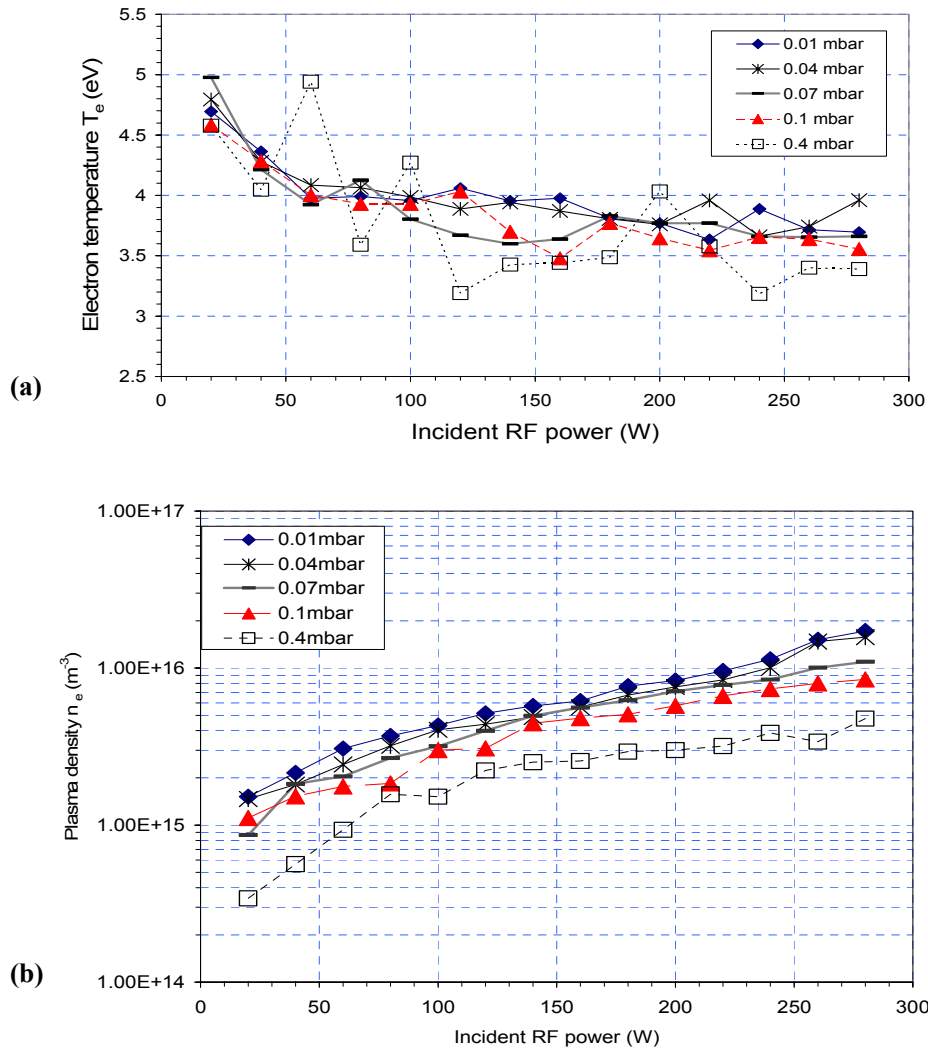


FIG. 6. (a) Electron temperature; and (b) plasma density are shown as functions of incident RF power at five different Argon gas pressures.

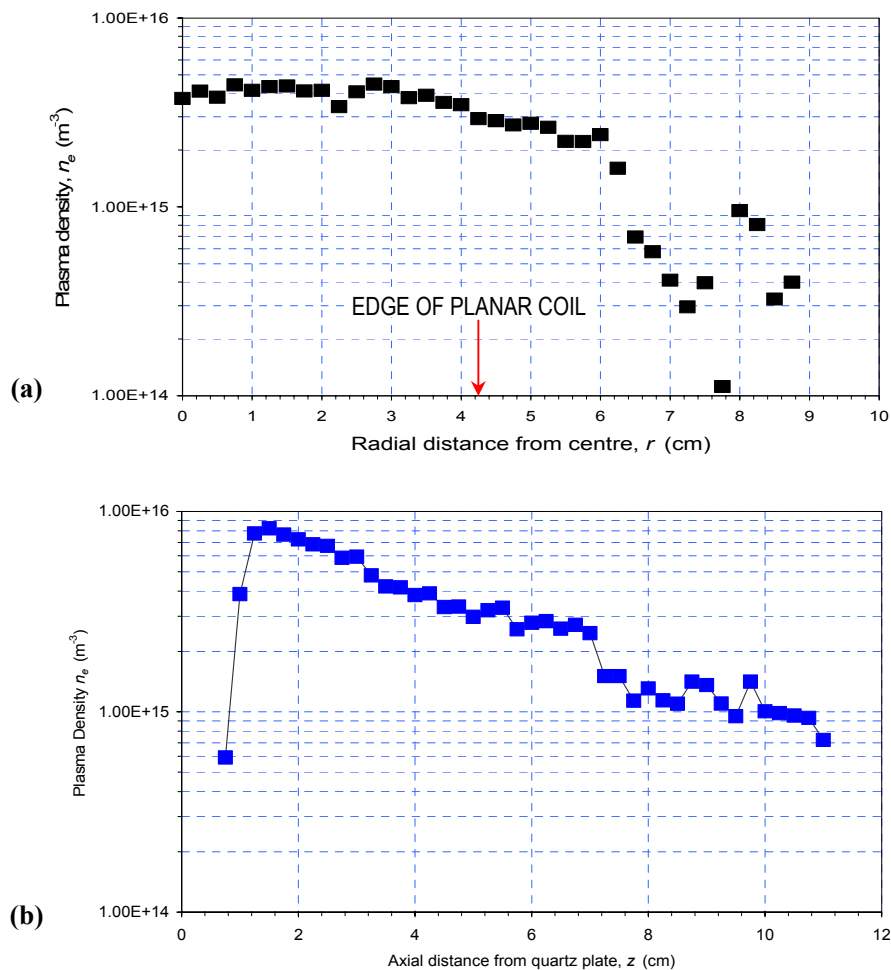


FIG. 7. (a) Radial distribution and (b) axial distribution of the plasma density in 0.1 mbar Argon at 100 W incident RF power.

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